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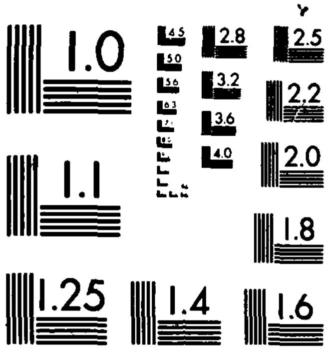

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MEDIATION AND AUTOMATIZATION

Edwin Hutchins

April 1987

ICS Report 8704

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Institute for Cognitive Science
University of California, San Diego
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This paper discusses the relationship between the mediation of task performance by some structure that is not inherent in the task domain itself and the phenomenon of automatization in which skilled performance becomes effortless or phenomenologically "automatic" after extensive practice. The use of a common simple explicit mediating device, a checklist, is described in detail. It is assumed that all skilled performances are initially mediated by some structure, either internal or external, and that the terms in the mediating structure provide constraints that can be used to evaluate behavior for its appropriateness. A parallel distributed processing view of cognition would lead us to expect as a consequence of repeated mediated task performance that a learning network will learn the sequence of states that constitute the task, and with sufficient practice may be able to move through them without the application of the constraints provided by the mediating structure. It is argues that this condition of no-longer-mediated performance is precisely what has been seen as automatized performances and that the changes that obviate the need for mediation are the processes underlying the development of skill automatization.

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Mediation and Automatization

EDWIN HUTCHINS

Mediation refers to a particular mode of organizing behavior with respect to some task by achieving coordination with a mediating structure that is not itself inherent in the domain of the task. That is, in a mediated performance, the actor does not simply coordinate with the task environment, instead, the actor coordinates with something else as well, something that provides structure that can be used to shape the actor's behavior. What this something else is, where it may be located, and how simultaneous coordination with it and some task relevant environment is achieved are central questions in understanding what sorts of creatures we humans are. Skill *automatization* refers to the process presumed to underlie the observation that skilled performance may become effortless or phenomenologically "automatic" after extensive practice. This note discusses some relationships between these two concepts based on the behavioral properties of "neurally inspired" models of cognitive processing. The first section attempts to explore the sorts of activities that are involved in the use of a simplk mediating artifact. Here I make two assumptions: (a) that all "skilled" performances are initially mediated by some structure, either internal or external, that provides some sort of description of the performance of the skill, and (b) that the descriptions in this mediating structure provide constraints on behavior; constraints that can be used to control behavior. The control may not be direct in the sense of producing behavior. The constraints need only permit the actor to evaluate behavior that has been produced and to judge whether or not it is appropriate. In the worst case the actor might behave randomly until an appropriate behavior was produced. In such a case, learning would be undirected and would surely be very slow, but it could still occur. The second section describes what a parallel distributed processing (PDP) or "connectionist" approach to cognition would lead us to expect as consequences of repeated mediated task performance. In brief, this approach leads us to expect that a neural apparatus will learn the sequence of states that constitute the task, and with sufficient practice may be able to move through them without the application of the constraints provided by the mediating structure. I will argue that this condition of no-longer-mediated performance is precisely what has been seen as automatized performance and that the changes that obviate the need for mediation are the processes underlying the development of skill automatization.

The phenomena of mediated performance are absolutely ubiquitous. For the purposes of exposition I have chosen as an example a simple explicit external mediation device, a checklist. Many tasks in our culture are mediated by checklists or checklist-like artifacts, but even considering all of them would not scratch the surface of the full range of mediated performance. Language, cultural knowledge, mental models, arithmetic procedures, and rules of logic are all mediating structures too. So are traffic lights, supermarket layouts, and the contexts we arrange for each other's behavior. Mediating structure can be embodied in artifacts, in ideas, in systems of social interaction, or in all of these at once. I have chosen the checklist because it is an artifact that provides a relatively explicit example of mediation for which a relatively simple exposition can be given.

A-1

CHECKLIST AS MEDIATING STRUCTURE

Consider an actor using a checklist to organize the performance of a task where it is essential that the actions of the performance be taken in a particular order and that all of the actions be taken before the performance is judged complete. In order to use a checklist as a guide to action, the task performer must coordinate with both the checklist and the environment in which the actions are to be taken. Achieving coordination with the checklist requires the actor to invoke procedures for the use of the checklist. These include reading skills and a strategy of sequential execution that permits the task performer to ensure that the steps will be done in the correct order and that each step will be done once and only once. The fixed linear structure of the checklist permits the user to accomplish this by simply keeping track of an index that indicates the first unexecuted (or last executed) item. Real checklists often provide additional features to aid in the maintenance of this index: boxes to tick when steps are completed, a window that moves across the checklist, etc. The mediating artifact has been designed with particular structural features that can be exploited by some procedure to produce a useful coordination. Such a procedure can be seen as meta-mediation, a mediating artifact that permits the use of some other mediating artifact. An actor always incurs some cognitive costs in coordinating with a mediating structure. But the savings of the mediated performance over the unmediated performance hopefully outweigh the costs of using it. The reduction of error or increase in efficiency obtained via the use of the checklist may compensate for the effort required to use it. For the unskilled performer, of course, the task may be impossible without the use of the checklist so the economy of mediated performance in that case is clear.

The first stage in the use of the checklist is depicted in Figure 1. The left-hand column of the figure contains relevant things inside the actor and the right-hand column contains relevant things in the environment of the actor. All of the things listed are brought into coordination with each other by the actor to achieve the described action. The items in UPPERCASE letters are the things that are meant to be shaped or brought into existence by the action. Figures 1 through 4 present a pseudo-sequential picture of the actual activities of the user of a checklist. Because the action described by each figure depends in some way on the actions in the previous figures, it is tempting to think of these as sequential stages. However, because of interactions among them in the doing of the task, they are better thought of as concurrent levels of activity than as stages.

In finding the next step to do in the checklist, the actor invokes the sequential execution strategy on the checklist to determine which step is the next one, and possibly to determine an index of the next step that can be remembered. There are two related issues concerning this index: where it is stored and what it contains. The index could be encoded in the memory of the actor, or the actor could take some action on the world, making a mark on the checklist itself for example, that acts as the index. The content of the index might be simply a mark on paper, a number if the steps are numbered, the lexical or

INSIDE	*OUTSIDE*
Sequential Strategy	Checklist (as a list of steps)
NEXT STEP INDEX	NEXT STEP

FIGURE 1. Finding the next step.

semantic content of the step description itself, or something else. Each of these alternatives requires a different procedure to implement the sequential execution strategy. For example, if the content of the step index is the lexical or semantic content of the step itself, then finding the next step and establishing the step index are the same action. If the content of the step index is a mark on a paper or a number to be recorded or remembered, then some action in addition to finding the next step must be undertaken to establish the step index. While the primary product of the application of this strategy is the determination of the next step to do, it is important to notice that either the checklist as an object in the environment or the procedure that implements the sequential execution strategy may also be changed as a consequence of the activities involved in finding the next step.

Having generated a step index (in whatever form) the actor can bring that index into coordination with the checklist to focus attention on the current step. While the goal of the use of the checklist as a mediating artifact is to ensure sequential control for the actions taken in the task domain, it is clear that the task of bringing the checklist into coordination with the domain of action may not itself be linearly sequential. For example, if a user loses track of the step index, in order to determine the next step to be taken, the user may go back to the beginning of the checklist and proceed through each step in the checklist, not executing it, but asking of the task world whether or not the expected consequences of the step's execution are present. When a step is reached whose consequences are not present in the task world, it may be assumed that it has not yet been executed. This is a simple illustration of the potential complexity of the meta-mediation that may be undertaken in the coordination of a mediating structure with a task world.

Once the current step has been identified, the user may coordinate its printed representation with shallow reading skills in order to produce an internal representation of what the step says in words. This is depicted in Figure 2. The shallow reading skills here refer to organized (possibly already automated) internal structures that can create internal representations of words from their external printed counterparts.[1] It is obvious that this may proceed concurrently with the stage of reading what the step means. However, I have separated shallow and deep readings primarily because shallow and deep readings produce different sorts of products that can be shown to exist independently. Thus, a user who does not understand the domain of action may know and be able to recall what a step "says" without having any idea at all of what it "means."

INSIDE	*OUTSIDE*
Next step index	Checklist (as a list of steps)
Shallow Reading	CURRENT STEP
"WHAT THE STEP SAYS" WORDS	

FIGURE 2. Finding what the step says.

[1] Whether this internal representation is primarily auditory or visual or something else, I do not know. The important thing is that it be capable of permitting the actor to "remember" the lexical content of the step at a later time.

Figuring out what a step means requires the coordination of what the step says with the task world via the mediation of a deeper sort of reading (see Figure 3). This deep reading relies on two internal structures, one that can provide semantic mappings from linguistic descriptions provided by the checklist to states in the world and another to provide readings of the task world to see what is there. What the words in the step description are thought to mean may depend upon the state of the task world that has been produced by prior steps. In this process it also becomes clear that the right way to think of this situation is not that the words and the world are coordinated by language in order to produce the meanings, but that the meanings, the world, and the words are all put in coordination with each other via the mediating structure of language. As we saw in Figure 1, the item in uppercase letters is in some sense the product of the activity, but the other items with which it is brought into coordination may be changed in the process of producing the product. Thus, the structure of language may be changed by its use, and what is thought to be in the world may be changed by describing it in a novel way. All of the structures provide constraints on the others, and all are to some extent malleable. The system composed of task performer, mediating structures, and task world settles into a solution that satisfies as many constraints as is possible.

Finally, having determined what the step means, the user of the checklist may take actions on (and in) the world to carry out the step. This is described in Figure 4. Whether the action should be placed inside or outside the actor is difficult to say. This is because actions taken on the environment involve phenomena inside and outside the actor and because for some mental acts the task world itself is inside. In any case, the meaning of the step, the action, and the task world are brought into coordination. Having completed this step the checklist user may find the next step and continue.

While following the checklist, high-level control of task-related behavior is given over in part to the structure of the mediating artifact. The interaction with the checklist produces for the actor a sequence of experiences of step descriptions. Each of these experiences may have several components: what the step says, what the step means, and the actions in the task world that carry out the step. While it might have seemed at first blush that the actor alternates coordinating with the checklist and coordinating with the world, the coordination with the two media is in fact simultaneous to the extent that understanding a step in the description may depend upon understanding the state of the world in which it is to be carried out. The experience of the meanings of the descriptions of the steps embeds experience of the task world, and the doing of the actions embeds the experience of the meaning of the task steps. The importance of this is that in this mediated performance the actor becomes a special sort of medium that can provide continuous coordination among several structured media. Looking at Figures 1 through 4,

INSIDE	*OUTSIDE*
"What the step says" words	
Language Deep Reading World Understanding	Task World
"WHAT THE STEP MEANS" IDEAS/IMAGES	

FIGURE 3. Discovering what the step means.

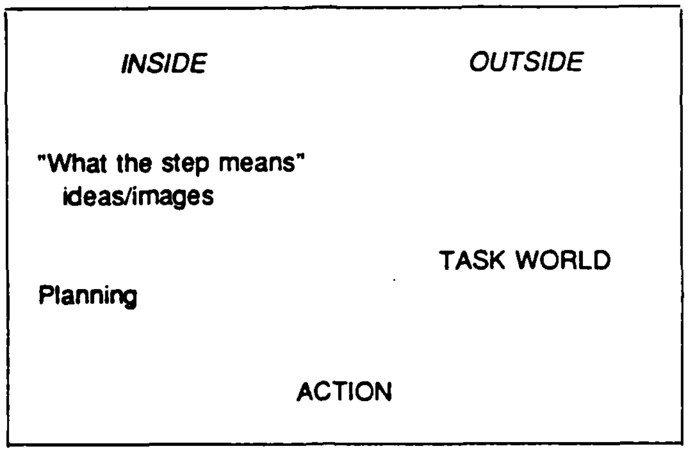

FIGURE 4. Performing the step.

we see that many layers of transformed mediating structure may lie between a simple mediating artifact like a checklist and a task performance.

CONSEQUENCES OF MEDIATED TASK PERFORMANCE

Parallel distributed processing (PDP) models of cognition assume an architecture of computation that is inspired by the general organization of neural networks in biological organisms.[2] A PDP system consists of a set of processing units and a set of unidirectional connections between the units. At each moment in time, each unit has an activation value. This activation is passed through the connections to other units in the system. Each connection has a *strength* that determines the amount of effect that the unit sending activation has on the unit receiving activation. The combined inputs to a unit from other units along with its own activation value determine its new activation value. If we were to force some subset of the units of the system to assume particular activation values, the effects of that input would propagate across the connections and the set of units as a whole would assume a pattern of activation that is determined by the combined effects of the structure of the input we forced upon it and the pattern of the strengths of the connections among the units. Such a pattern of activation across the set of units as a whole can be interpreted as a state of the system. When we are thinking of PDP networks as cognitive systems, a state as a pattern of activation across the units corresponds to a representation. Such a simple system can do pattern matching and can complete patterns from incomplete inputs. Which states the system assumes in response to which inputs is governed by the pattern of connectivity among the units. What the system *knows* is encoded in the connections among the units rather than in the activation states the units assume. The strengths of the connections among the units are not fixed. Instead, they can be modified on the basis of experience. This means that the state the system assumes in response to an input can change, or, put in other words, the system can learn to respond to an input in a particular way. If the units that are the output of the network are connected back into the network's own input, the network can be trained on a sequence of states and will learn to transition through the sequence automatically. With appropriate training, the occurrence of each state in the network becomes the condition that causes the network to assume the following state. Notice that while the states of the

[2] There is not sufficient space here to adequately explain how PDP systems actually work. In the following paragraphs, I outline some of their more interesting functional properties. I refer the interested reader to Rumelhart and McClelland, 1986.

network may be taken as explicit representations, the way the network gets from state to state is not explicitly represented anywhere in the network. It is implicit in the pattern of connectivity among units.

Imagine three such neural networks: a lexical network dedicated to representing what the steps of the checklist say, a semantic network dedicated to representing what the steps mean, and an action network dedicated to effecting the actions taken in the task world. All three of these may be working concurrently. When the checklist user performs a step, all three networks are activated. The shallow reading of the step itself produces a state in the lexical network. The working-out of the meaning of the step produces a state in the semantic network, and the performance of the actions that constitute the doing of the step produce states in the action network. The states in these networks are related to each other by the mediating structures (listed in Figures 1 through 4) that propagate state from one network to the next (see Figure 5). Let us now consider what might happen to this system with repeated performance of the task. As the user of the checklist reads each step in turn, the network that is dedicated to representing what the steps say is driven through a sequence of states that is repeated each time the checklist is followed. As a consequence, with repetition, the network learns the sequence of states produced by the shallow reading of the checklist, thereby internalizing the checklist. Here, by "internalizing the checklist" I mean specifically the development of a network that when placed in a state corresponding to the experience of "what Step N says" will transition automatically to a state corresponding to the experience of "what Step N+1 says."

Once such an internalized version of the checklist is developed, it may become the controlling structure for subsequent performances. This is shown in Figure 6. This amounts to the task performer having learned what the checklist says so that instead of reading the next step, he can "remember" what the next step says, use that to construct the meaning of the next step, and use that meaning to organize an action. A performance guided by the memory of the checklist is still a mediated task performance, but the mediating structure is now internal rather than external. The lexical network that encodes what the steps of the checklist say provides explicit representations of the steps of the procedure. It can move through a sequence of states, each of which corresponds to the experience of reading what a step on the checklist says. Moving from external to internal mediation also introduces new possibilities for the relations between the actor and the environment because the environment no longer need contain the mediating structure. The actor can deal with a wider range of environments. If the external mediating structure has been provided by the activities of another person, once the actor had internalized the structure provided by the other, he could act alone.[3]

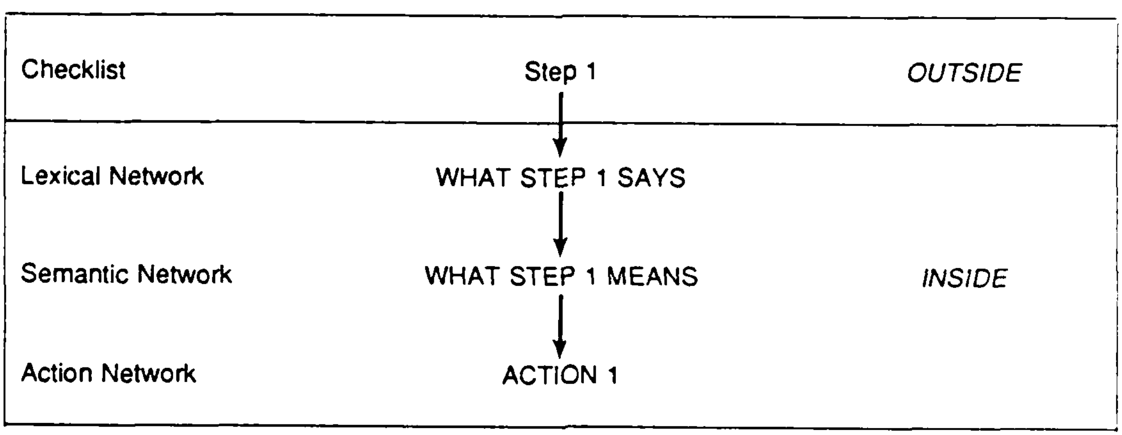

FIGURE 5. The networks activated in the performance of a step.

[3] This echoes Vygotsky's general genetic law of development with the two appearances of the mediating structure, one interpsychological and the other intrapsychological.

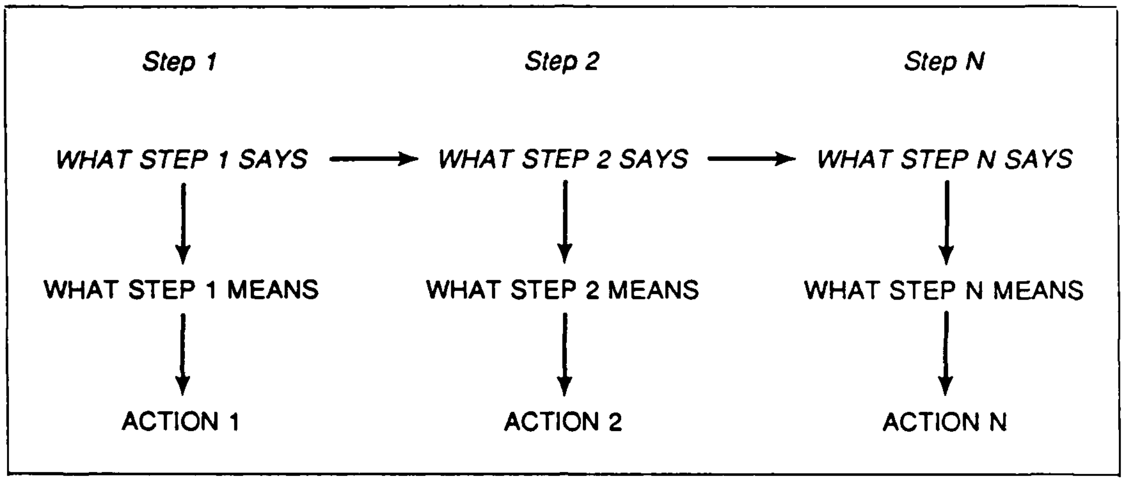

FIGURE 6. Internalization of the checklist by the lexical network. The lexical network has internalized the succession of states corresponding to the experience of reading the steps of the checklist. The horizontal arrows represent the learned state transitions in the lexical network. The vertical arrows represent the mediated propagation of state from the lexical to the semantic network via language skills and from the semantic to the action network via planning and motor skills.

Of course, at the same time that the neural network dedicated to the representation of what the steps say is being driven through a series of states, so is the neural network dedicated to representing the meanings of the steps. This is shown in Figure 7. Once this semantic network has been trained, the actor can remember the meanings of the steps, if necessary, without reference to the memory of what the steps say. Since that other structure is around, however, and since people are unrelentingly opportunistic it is likely that both the memory of the meaning of the step and the meaning derived from interpreting the memory of what the step says will be used in concert to determine the meaning of the step. Furthermore, a task performer may learn about the semantics of the domain and use that additional knowledge as yet another internal mediating structure in a subtask of deriving constraints on the meaning of the next step to help in the reconstruction process that is remembering. This is an argument for the value of conceptual learning beyond rote learning.

But something else is happening too. In the use of both the external checklist and the internalized checklist, the neural apparatus involved in the performance of the task is driven through a sequence of states. Because of the nature of the structured interaction of the task performer with the environment, the sequence of states is repeated more or less consistently each time the checklist is followed. The network begins to encode the sequential relations among the successive states. Something of the organization of the $n+1$th state is in the potential of the network when the nth state is present. Thus, the action network begins to internalize the sequence of steps of the task in a different sense than the internalization of the words or meanings of the checklist itself. This latter internalization is implicit whereas the internalization of the lexical ad the semantic representations were explicit. With this encoding of the sequence represented implicitly in the connections of the action network, the network, once placed in State 1, can *do* the task automatically without reference to any explicit representation of the sequence. The mediated performances leading up to this state could be thought of as training trials for the network that produces the action. The system has now reached the condition described by Figure 8. In this condition, for a normal task performance, the action network no longer needs the organizing constraints of the mediating structure. Once placed in the initial state, the action network simply transitions through the states that constitute the doing of the task. This is the nature of automatized skill performances: Automatized performances are performances that no longer utilize the organizing constraints of the mediating structure. Of course, if exceptional circumstances arise in the task world, the automatized performance may fail, requiring additional recourse to the mediating structure.

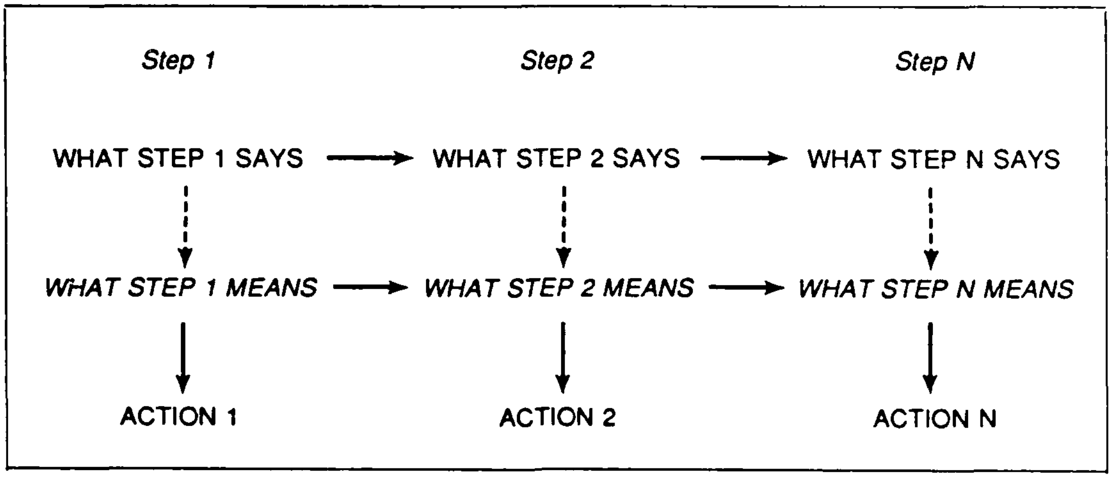

FIGURE 7. Automatization of the step meaning sequence by the semantic network. The semantic network has internalized the succession of states corresponding to the meanings of the steps of the checklist. The solid vertical arrows represent the mediated propagation of state from the semantic to action network. The dashed vertical arrows represent the available but not normally needed mediated propagation of state from the lexical network to the semantic network.

It is important to see that internalized memory of the checklist must become an automatized system before it can be used alone to control the states of the action network. Internalized mediation systems, while having explicit representational content in their states, rely for their controlling behavior on automatized implicit encodings of relations among their states. The issue of what is implicit and what is explicit depends upon the question being asked. The internalized memory for the checklist consists of states that represent explicit descriptions of the actions to be taken. But the sequential relations among those step descriptions are implicitly encoded in the pattern of connectivity of the lexical network much as the sequential relations among the step descriptions in the external checklist were implicitly encoded in their spatial relations on the checklist artifact itself. Consider briefly another common mediating structure, alphabetical order. It is used in many storage and retrieval schemes in our culture, so pains are taken to ensure that children learn it. In learning the alphabet song, the child is developing an explicit internalized automatized version of the alphabet structure. The content of the states, the words of the song, are explicit, but the sequential relations among them—which were provided by another mediating system, a teacher—are implicit. A child who knows the song can tell you what comes after *P* (perhaps after singing the first 17 letters) but that same child will have a difficult time saying why *Q* follows *P*. There is simply no explicit representation of that in what the child knows.

The same thing would be true for the meanings of the steps were it not for the potential mediating role of conceptual knowledge in the task domain. If conceptual knowledge is tied to the meanings of the steps, some other network in the system may assume states that explicitly represent a reason why Step $N + 1$ follows Step N. However, such a mediating structure need not be learned before the sequence of meanings of the steps is learned. Sometimes we discover *why* we do some task the way we do long after we have learned to do the task itself.

A common observation concerning automatized skill is that skilled performers may have difficulty saying how it is they do what they do. Two reasons for this fall out of this analysis. First, the automatized action network for the checklist is a way of producing in the relation of the person to the environment a sequence of actions that constitute the doing of the steps described by the checklist. Because it encodes a relationship between the person and the environment, the execution of the checklist by the automatized action network requires the cooperation of the environment in a way that remembering the checklist does not. For example, the attempt to do a step can be frustrated by the lack in the environment of something required by the step. Yet one may remember a description of a step even though

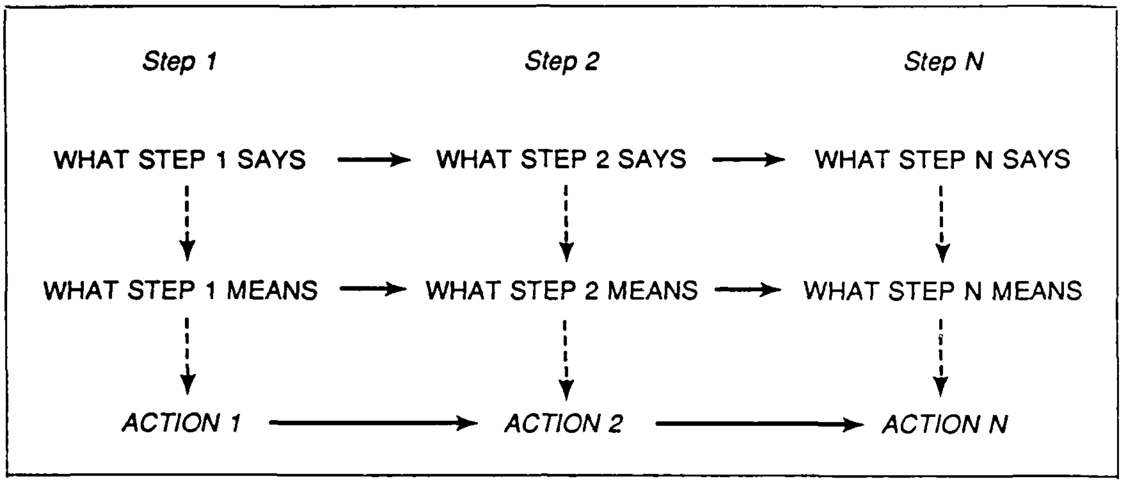

FIGURE 8. Automatization of the action sequence by the action network. The action network has internalized the succession of states corresponding to the actions taken in the task world. There is no longer a need for any mediation in the task performance. The entire structure is present, however, and could be invoked following any of the pathways present. The dashed vertical arrows represent not normally needed mediated propagation of state from the lexical network through the semantic network to the action network.

the conditions required to carry it out are absent. In the example above, the actor may be forced by the lack of the required condition to do some other actions in preparation for the previously frustrated step. In giving an account of how to do a task, the task performer must assume a world, or perhaps more correctly, the report itself implies a world in which the described actions make sense. Except where the task in question occurs in a very stable set of environments, the assumed world is certain to differ from many of the actual worlds in which the task is attempted and the description will therefore fail for many of the actual worlds in which the task is performed. Second, the reports skilled performers can give are generally based on the mediating structures that were used to control their behavior while they were acquiring automatized skill. The accounts that are given, being descriptions of mediating structure, may be just what is needed to communicate the skill from one person to another because the only way to produce the automatized skill is to have the network learn it from experience and the only way for a novice to experience it is by use of mediating structure. However, if the memory for the mediating structure has atrophied as a result of long disuse during automatized performance, when we ask an expert how something is done, there may simply be no meaningful answer to be given. The automated system does what it has been trained to do, but it has no explicit representation of what it is doing. The *representation* of what it is doing exists only in the apparatus that provided the training, that is, the mediating structure that is now degraded.

Another situation that results in the expert task performer being unable to account for his or her own task performance arises when the mediating structure is present as a set of constraints in the environment that shape the development of the action network directly without the development of internalizations of explicit mediating representations. This seems to be the case for many motor skills. When asked to describe how the skill is performed, such an expert may describe events in which the skill was manifested. One view of such a response might be that the expert is being uncooperative, but when we understand that the mediating structure was in the environment of the skill acquisition, we see that describing events in which the skill was manifested is the best the expert can do to describe the mediating structure under which the skill developed.

With this example I have attempted to highlight the complexity and richness of interaction of mediation structures of different sorts in the performance of what seemed at the outset to be a relatively simple mediated task performance. I don't think this analysis should lead us to change our minds about the relative simplicity of using checklists. On the contrary I hope it heightens our awareness of the diversity of kinds of mediating structure that come into play in everyday cognitive activities. In order to get useful mental work done, of course, the actor must be capable of bringing these structures into coordination with each other. As we saw with the coordination of the checklist with the task world, bringing mediating structures into coordination may require still more (meta-)mediating structures. The consequences of the lack of this ability are encoded in our folk wisdom about the differences between "book learning" and experience. One may have complete mastery over a major mediating structure for some task, but no development whatever of the meta-mediation required to put it to work in a real task environment.

In this view, what we learn and what we know and what our culture knows for us in the form of the structure of artifacts and social organizations are these hunks of mediating structure. Thinking consists of bringing these structures into coordination with each other such that they can shape (and be shaped by) each other. The thinker in this world is a very special medium that can provide coordination among many structured media, some internal, some external, some embodied in artifacts, some in ideas, and some in social relationships.

ICS Technical Report List

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8301. David Zipser. *The Representation of Location.* May 1983.

8302. Jeffrey Elman and Jay McClelland. *Speech Perception as a Cognitive Process: The Interactive Activation Model.* April 1983. Also published in N. Lass (Ed.), *Speech and language: Volume 10*, New York: Academic Press, 1983.

8303. Ron Williams. *Unit Activation Rules for Cognitive Networks.* November 1983.

8304. David Zipser. *The Representation of Maps.* November 1983.

8305. The HMI Project. *User Centered System Design: Part I, Papers for the CHI '83 Conference on Human Factors in Computer Systems.* November 1983. Also published in A. Janda (Ed.), *Proceedings of the CHI '83 Conference on Human Factors in Computing Systems.* New York: ACM, 1983.

8306. Paul Smolensky. *Harmony Theory: A Mathematical Framework for Stochastic Parallel Processing.* December 1983. Also published in *Proceedings of the National Conference on Artificial Intelligence, AAAI-83*, Washington DC, 1983.

8401. Stephen W. Draper and Donald A. Norman. *Software Engineering for User Interfaces.* January 1984. Also published in *Proceedings of the Seventh International Conference on Software Engineering*, Orlando, FL, 1984.

8402. The UCSD HMI Project. *User Centered System Design: Part II, Collected Papers.* March 1984. Also published individually as follows: Norman, D.A. (1984), Stages and levels in human-machine interaction, *International Journal of Man-Machine Studies, 21*, 365-375; Draper, S.W., The nature of expertise in UNIX; Owen, D., Users in the real world; O'Malley, C., Draper, S.W., & Riley, M., Constructive interaction: A method for studying user-computer-user interaction; Smolensky, P., Monty, M.L., & Conway, E., Formalizing task descriptions for command specification and documentation; Bannon, L.J., & O'Malley, C., Problems in evaluation of human-computer interfaces: A case study; Riley, M., & O'Malley, C., Planning nets: A framework for analyzing user-computer interactions; all published in B. Shackel (Ed.), *INTERACT '84, First Conference on Human-Computer Interaction*, Amsterdam: North-Holland, 1984; Norman, D.A., & Draper, S.W., Software engineering for user interfaces, *Proceedings of the Seventh International Conference on Software Engineering*, Orlando, FL, 1984.

8403. Steven L. Greenspan and Eric M. Segal. *Reference Comprehension: A Topic-Comment Analysis of Sentence-Picture Verification*. April 1984. Also published in *Cognitive Psychology, 16*, 556-606, 1984.

8404. Paul Smolensky and Mary S. Riley. *Harmony Theory: Problem Solving, Parallel Cognitive Models, and Thermal Physics*. April 1984. The first two papers are published in *Proceedings of the Sixth Annual Meeting of the Cognitive Science Society*, Boulder, CO, 1984.

8405. David Zipser. *A Computational Model of Hippocampus Place-Fields*. April 1984.

8406. Michael C. Mozer. *Inductive Information Retrieval Using Parallel Distributed Computation*. May 1984.

8407. David E. Rumelhart and David Zipser. *Feature Discovery by Competitive Learning*. July 1984. Also published in *Cognitive Science, 9*, 75-112, 1985.

8408. David Zipser. *A Theoretical Model of Hippocampal Learning During Classical Conditioning*. December 1984.

8501. Ronald J. Williams. *Feature Discovery Through Error-Correction Learning*. May 1985.

8502. Ronald J. Williams. *Inference of Spatial Relations by Self-Organizing Networks*. May 1985.

8503. Edwin L. Hutchins, James D. Hollan, and Donald A. Norman. *Direct Manipulation Interfaces*. May 1985. Also published in D. A. Norman & S. W. Draper (Eds.), *User Centered System Design: New Perspectives on Human-Computer Interaction*, 1986, Hillsdale, NJ: Erlbaum.

8504. Mary S. Riley. *User Understanding*. May 1985. Also published in D. A. Norman & S. W. Draper (Eds.), *User Centered System Design: New Perspectives on Human-Computer Interaction*, 1986, Hillsdale, NJ: Erlbaum.

8505. Liam J. Bannon. *Extending the Design Boundaries of Human-Computer Interaction*. May 1985.

8506. David E. Rumelhart, Geoffrey E. Hinton, and Ronald J. Williams. *Learning Internal Representations by Error Propagation*. September 1985. Also published in D. E. Rumelhart, J. L. McClelland, & the PDP Research Group, *Parallel Distributed Processing: Explorations in the Microstructure of Cognition: Vol. 1. Foundations*, 1986, Cambridge, MA: Bradford Books/MIT Press.

8507. David E. Rumelhart and James L. McClelland. *On Learning the Past Tense of English Verbs*. October 1985. Also published in J. L. McClelland, D. E. Rumelhart, & the PDP Research Group, *Parallel Distributed Processing: Explorations in the Microstructure of Cognition: Vol. 2. Psychological and Biological Models*, 1986, Cambridge, MA: MIT Press/Bradford Books.

8601. David Navon and Jeff Miller. *The Role of Outcome Conflict in Dual-Task Interference*. January 1986.

8602. David E. Rumelhart and James L. McClelland. *PDP Models and General Issues in Cognitive Science*. April 1986. Also published in D. E. Rumelhart, J. L. McClelland, & the PDP Research Group, *Parallel Distributed Processing: Explorations in the Microstructure of Cognition. Vol. 1: Foundations*, 1986, Cambridge, MA: MIT Press/Bradford Books.

8603. James D. Hollan, Edwin L. Hutchins, Timothy P. McCandless, Mark Rosenstein, and Louis Weitzman. *Graphical Interfaces for Simulation*. May 1986. To be published in W. B. Rouse (Ed.), *Advances in Man-Machine Systems* (Vol. 3). Greenwich, CT: Jai Press.

8604. Michael I. Jordan. *Serial Order: A Parallel Distributed Processing Approach*. May 1986.

8605. Ronald J. Williams. *Reinforcement Learning in Connectionist Networks: A Mathematical Analysis*. June 1986.

8606. David Navon. *Visibility or Disability: Notes on Attention*. June 1986.

8607. William Appelbe, Donald Coleman, Allyn Fratkin, James Hutchison, and Walter J. Savitch. *Porting UNIX to a Network of Diskless Micros*. June 1986.

8608. David Zipser. *Programming Neural Nets to Do Spatial Computations*. June 1986. To be published in N. E. Sharkey (Ed.), *Advances in Cognitive Science* (Vol. 2). Norwood, NJ: Ablex.

8609. Louis Weitzman. *Designer: A Knowledge-Based Graphic Design Assistant*. July 1986.

8610. Michael C. Mozer. *RAMBOT: A Connectionist Expert System That Learns by Example*. August 1986.

8611. Michael C. Mozer. *Early Parallel Processing in Reading: A Connectionist Approach*. December 1986. To be published in M. Coltheart (Ed.), *Attention and Performance XII*. Hillsdale, NJ: Lawrence Erlbaum Associates.

8701. Jeffrey L. Elman and David Zipser. *Learning the Hidden Structure of Speech*. February 1987.

8702. Garrison W. Cottrell, Paul Munro, and David Zipser. *Image Compression by Back Propagation: An Example of Extensional Programming*. February 1987.

8703. Edwin Hutchins. *Metaphors for Interface Design*. April 1987. Paper presented at NATO-sponsored Workshop on Multimodal Dialogues Including Voice, Venaco, Corsica, France, September 1986.

8704. Edwin Hutchins. *Mediation and Automatization*. April 1987. Also published in *The Quarterly Newsletter of the Laboratory of Comparative Human Cognition*, 1986, 8, 47-58.

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ONR-8001. Donald R. Gentner, Jonathan Grudin, and Eileen Conway. *Finger Movements in Transcription Typing*. May 1980.

ONR-8002. James L. McClelland and David E. Rumelhart. *An Interactive Activation Model of the Effect of Context in Perception: Part I*. May 1980. Also published in *Psychological Review, 88,5*, pp. 375-401, 1981.

ONR-8003. David E. Rumelhart and James L. McClelland. *An Interactive Activation Model of the Effect of Context in Perception: Part II*. July 1980. Also published in *Psychological Review, 89, 1*, pp. 60-94, 1982.

ONR-8004. Donald A. Norman. *Errors in Human Performance*. August 1980.

ONR-8005. David E. Rumelhart and Donald A. Norman. *Analogical Processes in Learning*. September 1980. Also published in J. R. Anderson (Ed.), *Cognitive skills and their acquisition*. Hillsdale, NJ: Erlbaum, 1981.

ONR-8006. Donald A. Norman and Tim Shallice. *Attention to Action: Willed and Automatic Control of Behavior*. December 1980.

ONR-8101. David E. Rumelhart. *Understanding Understanding*. January 1981.

ONR-8102. David E. Rumelhart and Donald A. Norman. *Simulating a Skilled Typist: A Study of Skilled Cognitive-Motor Performance*. May 1981. Also published in *Cognitive Science, 6*, pp. 1-36, 1982.

ONR-8103. Donald R. Gentner. *Skilled Finger Movements in Typing*. July 1981.

ONR-8104. Michael I. Jordan. *The Timing of Endpoints in Movement*. November 1981.

ONR-8105. Gary Perlman. *Two Papers in Cognitive Engineering: The Design of an Interface to a Programming System and MENUNIX: A Menu-Based Interface to UNIX (User Manual)*. November 1981. Also published in *Proceedings of the 1982 USENIX Conference*, San Diego, CA, 1982.

ONR-8106. Donald A. Norman and Diane Fisher. *Why Alphabetic Keyboards Are Not Easy to Use: Keyboard Layout Doesn't Much Matter*. November 1981. Also published in *Human Factors, 24*, pp. 509-515, 1982.

ONR-8107. Donald R. Gentner. *Evidence Against a Central Control Model of Timing in Typing*. December 1981. Also published in *Journal of Experimental Psychology: Human Perception and Performance, 8*, pp. 793-810, 1982.

ONR-8201. Jonathan T. Grudin and Serge Larochelle. *Digraph Frequency Effects in Skilled Typing*. February 1982.

ONR-8202. Jonathan T. Grudin. *Central Control of Timing in Skilled Typing*. February 1982.

ONR-8203. Amy Geoffroy and Donald A. Norman. *Ease of Tapping the Fingers in a Sequence Depends on the Mental Encoding*. March 1982.

ONR-8204. LNR Research Group. *Studies of Typing from the LNR Research Group: The role of context, differences in skill level, errors, hand movements, and a computer simulation*. May 1982. Also published in W. E. Cooper (Ed.), *Cognitive aspects of skilled typewriting*. New York: Springer-Verlag, 1983.

ONR-8205. Donald A. Norman. *Five Papers on Human-Machine Interaction*. May 1982. Also published individually as follows: Some observations on mental models, in D. Gentner and A. Stevens (Eds.), *Mental models*, Hillsdale, NJ: Erlbaum, 1983; A psychologist views human processing: Human errors and other phenomena suggest processing mechanisms, in *Proceedings of the International Joint Conference on Artificial Intelligence*, Vancouver, 1981; Steps toward a cognitive engineering: Design rules based on analyses of human error, in *Proceedings of the Conference on Human Factors in Computer Systems*, Gaithersburg, MD, 1982; The trouble with UNIX, in *Datamation*, *27,12*, November 1981, pp. 139-150; The trouble with networks, in *Datamation*, January 1982, pp. 188-192.

ONR-8206. Naomi Miyake. *Constructive Interaction*. June 1982.

ONR-8207. Donald R. Gentner. *The Development of Typewriting Skill*. September 1982. Also published as Acquisition of typewriting skill, in *Acta Psychologica*, *54*, pp. 233-248, 1983.

ONR-8208. Gary Perlman. *Natural Artificial Languages: Low-Level Processes*. December 1982. Also published in *The International Journal of Man-Machine Studies*, *20*, pp. 373-419, 1984.

ONR-8301. Michael C. Mozer. *Letter Migration in Word Perception*. April 1983. Also published in *Journal of Experimental Psychology: Human Perception and Performance*, *9*, *4*, pp. 531-546, 1983.

ONR-8302. David E. Rumelhart and Donald A. Norman. *Representation in Memory*. June 1983. To appear in R. C. Atkinson, G. Lindzey, & R. D. Luce (Eds.), *Handbook of experimental psychology*. New York: Wiley (in press).

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